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A Study of the Longevity and Operational Reliability of Goddard Spacecraft: 1960-1980

Edward F. Shockey

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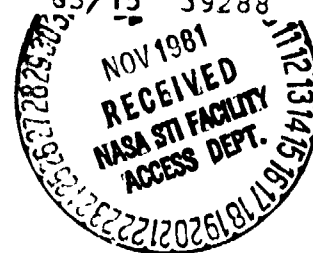
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Goddard Space Flight Center
Greenbelt, Maryland 20771

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INTRODUCTION

Aside from being a matter of general historic interest, the analysis of the performance of spacecraft in orbit provides a means to: 1) quantify progress, 2) identify problem areas, 3) aid in evaluating the effectiveness of flight assurance and reliability management practices, and 4) establish empirical relationships which can be used in forecasting future mission results and in planning management strategies. As longer and longer missions are planned, and more management options become available (or even mandated as in the case of the new STS payload classification scheme), these objectives become more important.

Spacecraft performance is defined by both how well and how long the spacecraft performs its assigned mission. Previous analyses of Goddard data have concentrated on how well missions have performed in terms of the frequency, criticality, and distribution of anomalies during flight. An update of this material is currently in preparation. The focus of the current study is spacecraft longevity and their consequent operational reliability. Data was compiled for 104 orbital missions having launch dates spanning the period from 1960 to 1980. Omitting irrelevant missions such as small piggybacks and missions for which Goddard did not have primary mission-success responsibility, such as the later International programs, this is a virtually complete roster of Goddard orbital missions. A brief description of these and other NASA missions may be found in "Satellite Handbook: A Record of NASA Space Missions 1958-1980", edited by A. Rosenthal, NASA/GSFC, 1981.

The analysis, which consists of a historical review of trends over the entire period and a more detailed examination of the more recent missions, is primarily statistical, but specific programs and problems are discussed as an aid in interpreting the data and placing it in perspective.

SOURCES, DEFINITIONS, AND LIMITATIONS OF THE DATA

The goal of the data collection effort was to compile information on the design life and useful lifetime of as many relevant Goddard satellites as possible. Data from project-related documents was utilized where available, but in some cases it was necessary to rely on secondary sources. "Useful lifetime" is defined as the period of time during which the spacecraft satisfied the objectives of its mission. This generally corresponds to its total active life, but in some cases spacecraft have been continued in service after serious functional losses in order to obtain secondary data. This situation, which applies primarily to some of the very early missions, led to occasional disagreement between sources on the useful lifetime of certain missions. These were resolved insofar as possible by consulting performance data, but there may be some remaining inconsistencies.

Spacecraft are generally not continued in service until functional capability is totally lost. The causes of mission termination may be classified as follows:

- Loss of Functional Capability:
 - Unexpected Failure
 - Wearout
 - Depletion of Consumables
- Reentry:
 - Planned (Mission Requirement)
 - Unplanned (Incorrect Orbit)
- Deactivation:
 - Excessive degradation
 - Mission completed
 - Funding Withdrawn
 - Obsolescence
 - Replacement

Since many spacecraft are terminated while still viable to a greater or lesser extent, it would be desirable to establish uniform reliability criteria, such as percentage degradation of performance,

and base the useful lifetime (which might then be termed "reliable lifetime") on those criteria. This has been done in cases where the spacecraft population is more homogeneous, such as the Canadian Telesat communications satellite program, where mission success requires that 12 of 14 available channels be operable, but is not easily accomplished for programs as varied in scope as Goddards. This is particularly true of the science missions.

Alternately, those missions which are terminated prior to failure might be considered as truncated data, that is as a "life test" which ended before failure occurred. This, however, would imply that no degradation had occurred during the life of the mission. In practice, it was found that most spacecraft had seriously degraded or had used up a major fraction of their consumable supplies by the time they were removed from service or reentered and therefore had completed a major portion of their potential lifetime. Hence, useful lifetime as a "de facto" measure of successful performance appears to be a good working hypothesis. To provide a convenient reference source and permit the interested reader to construct his own analyses, the entire data base including overall active life and data sources is shown in Appendix A. Pertinent launch vehicle data is shown in Appendix B.

GENERAL HISTORY AND TRENDS

Due to limitations in the available technology and in knowledge of the hazards of the space environment, in the early days of the space age orbital missions usually terminated by catastrophic failure or depletion of non-renewable supplies after a few weeks or months in orbit. Since these missions were essentially engineering feasibility studies, however, with limited scientific objectives, these lifetimes were generally more than adequate to achieve the desired objectives. Although some missions were assigned goals of as long as one year as early as 1961, through 1964 many included timers designed to turn off the spacecraft after a year in orbit in order to avoid cluttering the RF channels with obsolete transmissions. These timers often did not work, however, and the missions were usually continued beyond the one year period if useful data were still being obtained. Through 1965, only one Goddard mission, Syncom I, which failed to return any data from space, was officially declared unsuccessful.

By the mid-sixties, spacecraft were beginning to achieve lifetimes of a year or more on a fairly regular basis, while at the same time significant advances had been made in space technology. The feasibility of achieving very long orbital lifetimes was demonstrated as early as 1966 by the Goddard mission Application Technology Satellite I (ATS-I), and by the JPL project Pioneer VI, both of which are still in limited service after 15 years in space. It was also during this period that the ambitious orbiting observatory programs Orbiting Astronomical Observatory (OAO) and Orbiting Geophysical Observatory (OGO), conceived in the early sixties, came to fruition. These were the first Goddard programs to exceed half a ton in weight (OAO actually weighed almost 2 tons) and also incorporated one of the major innovations of the era, three-axis attitude control stabilization, which enabled spacecraft to be pointed precisely at a specific object in space. While the first OAO suffered a power failure at orbital injection, thereby becoming the second and final Goddard mission to fail to return any useful data from space, two follow-on missions were highly successful. The second of these, nicknamed Copernicus, was only recently deactivated after eight and a half years of excellent service.

The first two OGO's experienced difficulties which prevented their achieving three-axis stabilization, as did a later mission, ATS-V. All three of these missions served long useful lives (ATS-V is still active) despite this problem, but were officially classified as unsuccessful. No subsequent Goddard mission has been classified unsuccessful by the Agency.

Throughout the sixties, design goals continued to be set at 6 months or one year for the most part, but spacecraft began to exceed these goals by increasingly wide margins.

By 1970, this led to an embarrassment of riches, as more data began to be received than could be processed within planned budget allocations. Technological obsolescence also became a factor in mission termination as second-generation spacecraft were placed into service.

At this point, the success of the program combined with increasing pressure on NASA budgets led to more flexible management policies wherein costs and the relative importance of each phase of

the flight assurance program were measured against project criticality and acceptable risk levels. Certain missions began to be designated as low cost/high risk, where some of the elements generally considered important to reliability were sacrificed in the interest of reducing costs. This approach, for example, typically calls for the elimination of block redundancy. Where no clear-cut designation of cost-risk trade off was imposed, each mission was nevertheless implicitly controlled in this regard by strict budget accountability, with the more critical missions being assigned the more generous budgets. This trend continued through the seventies, and has now been formalized for Shuttle payload applications in a NASA management instruction which designates four classes of payloads discriminated by four levels of flight assurance requirements.

Another trend in the seventies resulting from the developing maturity of space technology was an increasing emphasis on applications satellites. Applications programs usually consist of a series of essentially identical spacecraft intended to provide a service such as communications or meteorological observations for a given number of years. There is a tendency on these programs to maintain older, partially degraded satellites in a standby mode as backups to the newer active satellites. Since many studies have shown that failure rates for inactive spacecraft are extremely low, this tends to extend the useful lives of these satellites.

GROWTH AND DISTRIBUTION OF USEFUL LIFETIMES

These trends are illustrated graphically in Figures 1 and 2. Figure 1 illustrates the growth in median lifetime of satellites launched in each calendar year through 1974, with later data being indeterminate since most of the more recent missions are still active. Note that the growth rate is not only persistent but surprisingly linear, and closely adheres to the trend line determined by regression analysis, particularly through the first decade. The somewhat greater scatter past 1970 may, in part, be caused by the increasing degree to which mission lifetime was becoming a matter of management options. The trend is described by the equation:

$$\hat{ML} = 0.1 + 0.361 (Y - 1960) \quad (1)$$

Where ML is the median life and Y is the calendar year.

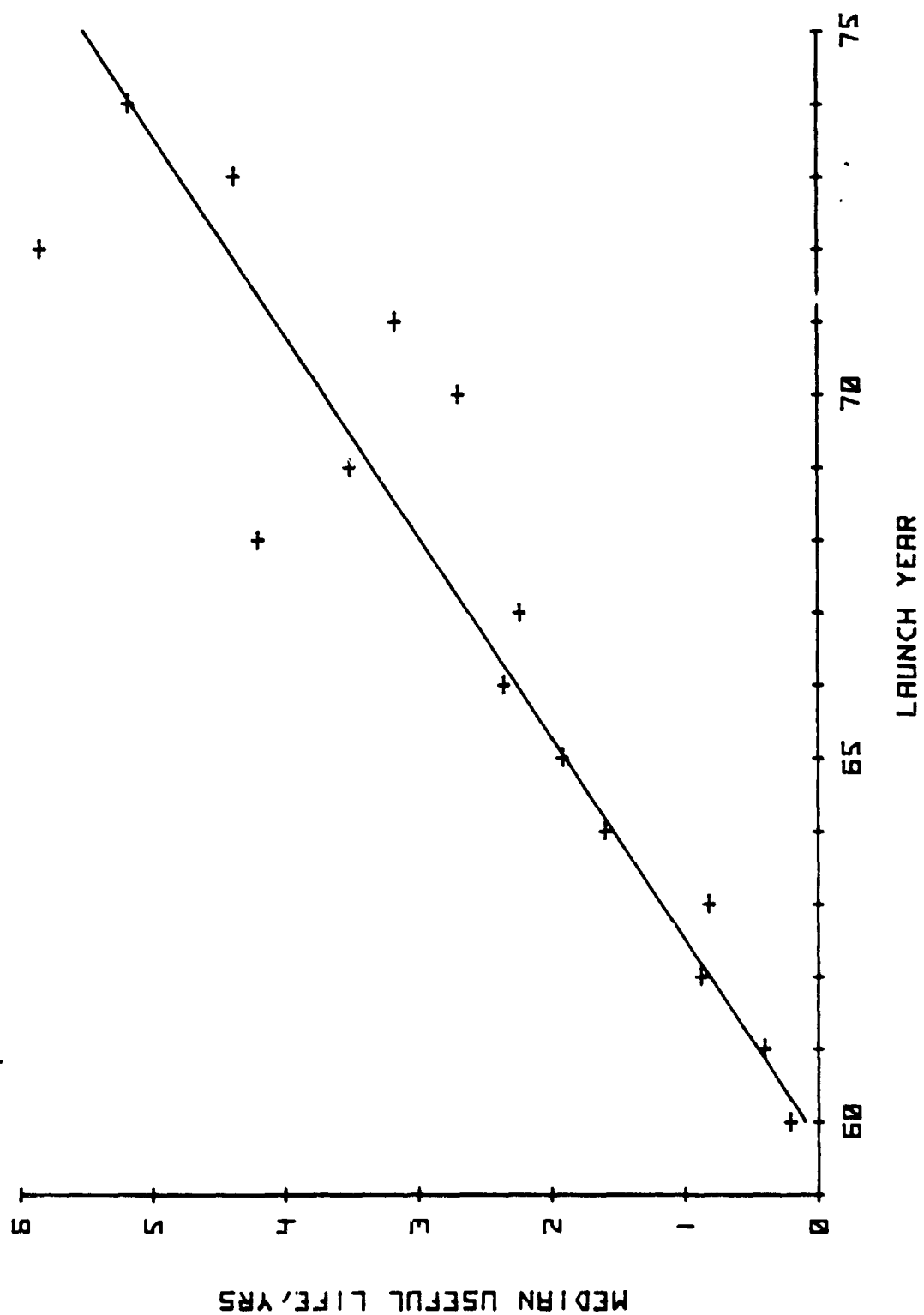


Figure 1. Annual Median Growth Rate Through 1975

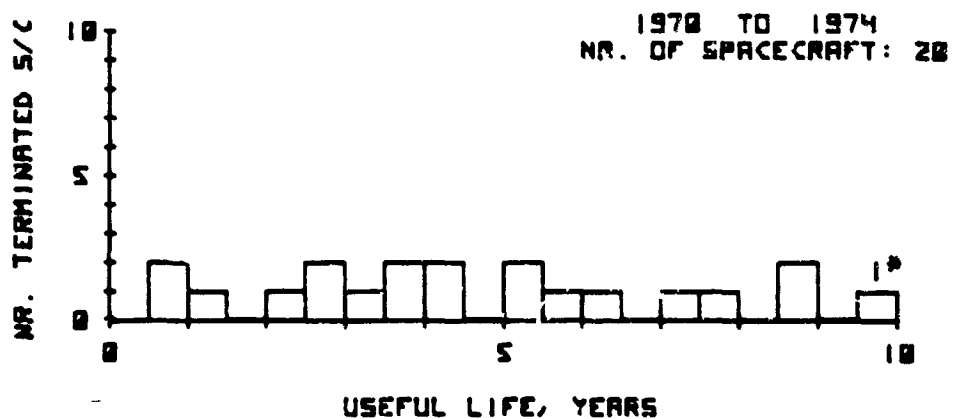
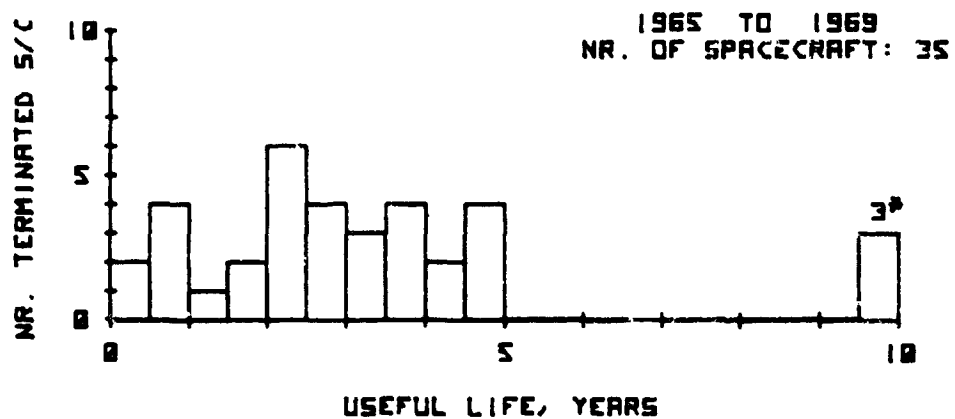
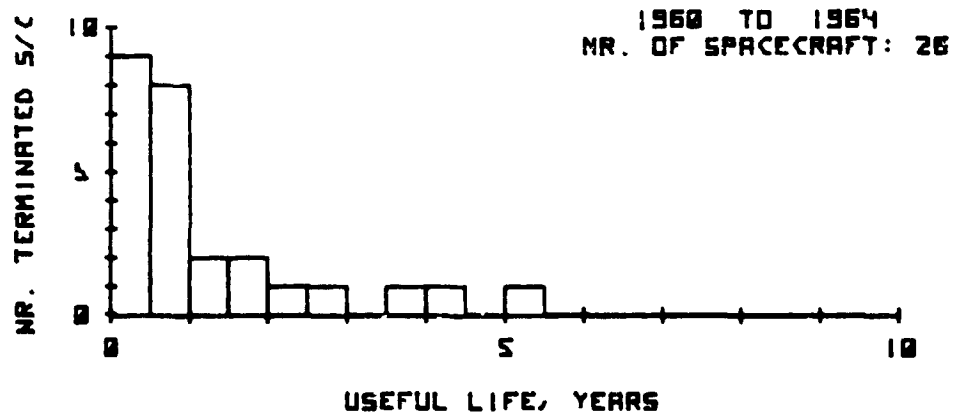
Table 1 presents the specific data for each year, including the mean values and maximum useful lifetimes achieved.

Table 1

LAUNCH YEAR	NO. OF S/C	USEFUL LIFETIME		
		MEDIAN	MEAN	MAX.
1960	3	.21	.33	.63
1961	3	.40	.44	.61
1962	8	.88	1.03	2.55
1963	5	.82	2.24	4.33
1964	7	1.59	1.67	5.23
1965	5	1.92	2.01	3.48
1966	9	2.36	3.72+	ACTIVE
1967	9	2.24	3.32+	ACTIVE
1968	5	4.20	3.63	4.95
1969	7	3.51	4.27+	ACTIVE
1970	4	2.70	3.99	10.00
1971	3	3.17	3.20	3.56
1972	6	5.84	5.26+	ACTIVE
1973	4	4.38	4.82+	ACTIVE
1974	3	5.17	5.43+	ACTIVE

Figure 2 illustrates the distribution of useful lifetimes achieved in the 5 year intervals 1960-64, 1964-1969, and 1970-74. The shapes of these curves are somewhat distorted by the fact that the data is not stationary, but since the growth rate was shown to be linear, the effect on each should be similar. It is interesting to compare these curves with the bathtub curve of classic reliability theory. It will be recalled that this curve consists of a period of declining failure rate, a period of constant failure rate, and a period of increasing failure rate, representing, in turn "infant mortality", random failure, and wearout. The distribution of failures in the wearout portion is usually considered to be Gaussian.

It will be observed that the 1960-64 data corresponds in shape to the infant mortality portion of the curve, in keeping with the fact that the industry itself was in its infancy. The 1965-69 data, although not as well defined, suggests a broad wear-out period between two and five years after



* NR. S/C LASTING 9.5 OR MORE YRS INCL IN THIS BAR

Figure 2. Distribution of Useful Lifetimes for Three Different Time Periods

launch. This corresponds to the typical wearout lives of continuously degradable devices such as batteries, tape recorders, solar array drives, scanning devices, etc, during this period, as well as indicating that spacecraft placed in high-drag orbits were surviving until reentry, which typically occurs in this time frame. The outliers in this group are the three communications satellites, Application Technology Satellite (ATS) 1, 3, and 5. Communication satellites typically have longer lifetime potential than other types since they have minimal pointing accuracy requirements, limited depth of battery discharge, and do not contain tape recorders and other electromechanical devices. Although the data suggests that infant mortality was no longer a problem in this time frame, as noted earlier three missions failed to achieve the desired three-axis stabilization and on that basis it could be said that the infant mortality problem had not been completely solved.

By the 1970-74 period, component wear-out lives had been broadened and extended to the point that they no longer cause a concentration of termination points, and the data takes on the appearance of the "random failure" portion of the bathtub curve. This indicates not that spacecraft were failing due to random causes, but that the reasons for mission termination had been randomized in that they had been expanded to include the management options discussed earlier.

USEFUL LIFE VS. DESIGN LIFE

A very fundamental measure of spacecraft performance may be established by comparing design lives with lifetimes actually achieved. To also see if there has been any temporal trend in this distribution, the data was divided into the same 5-year intervals used in Figure 2. The results are shown in Figures 3, 4, and 5. Points to the left of the diagonal lines correspond to spacecraft which failed to meet their design goals.

Previous investigators of spacecraft lifetime data have concluded that there is no correlation between design life and useful life (Reference 1, 2, 3). By dividing the Goddard data into 5-year intervals, however, it is possible to detect certain trends. In the 1960-64 period, for example, extension of design lives to one year seem to have been premature, since the majority of missions

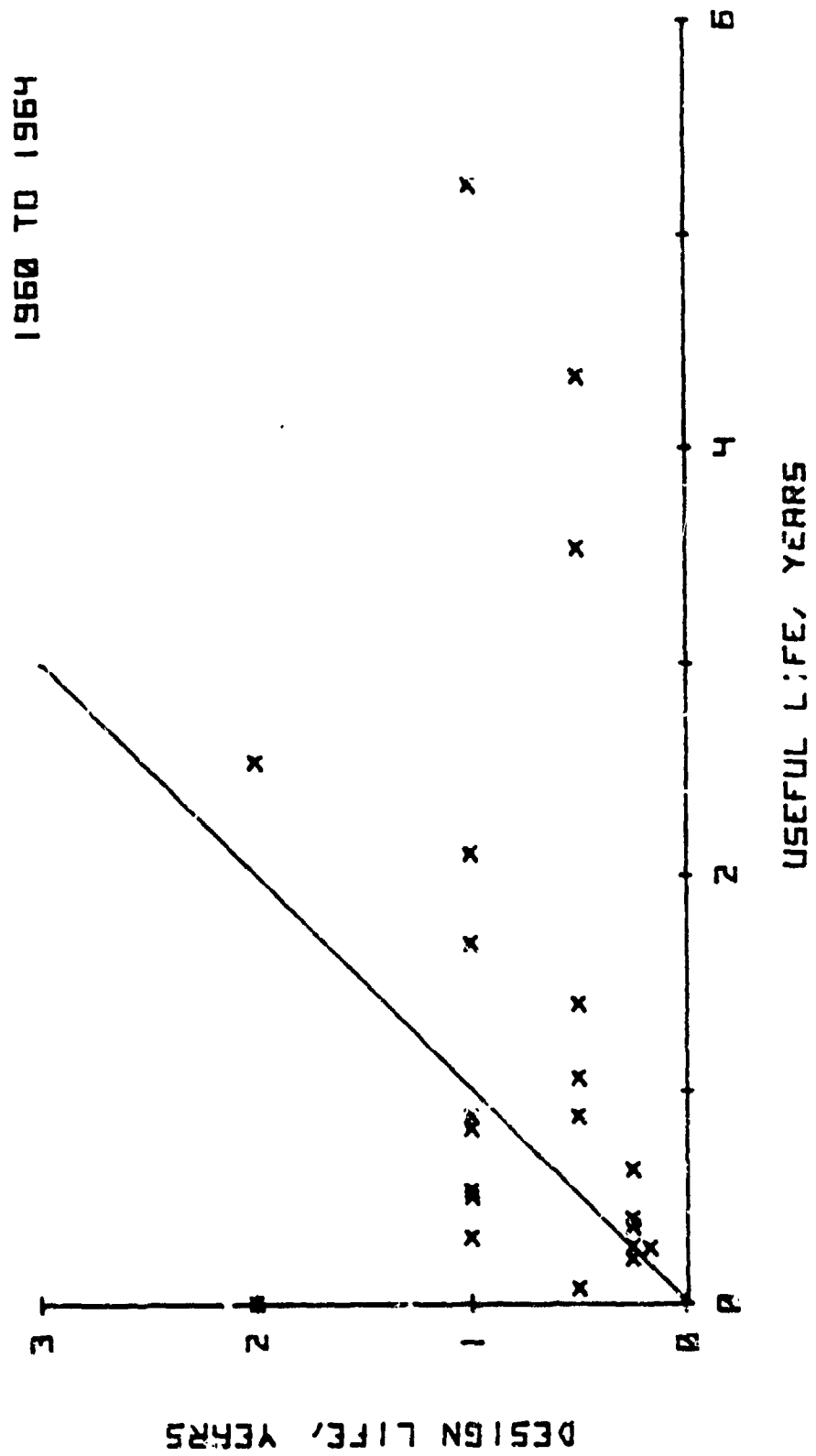


Figure 3. Comparison of Design Life and Achieved Useful Life of Spacecraft Launched 1960 Through 1964

1965 TO 1969

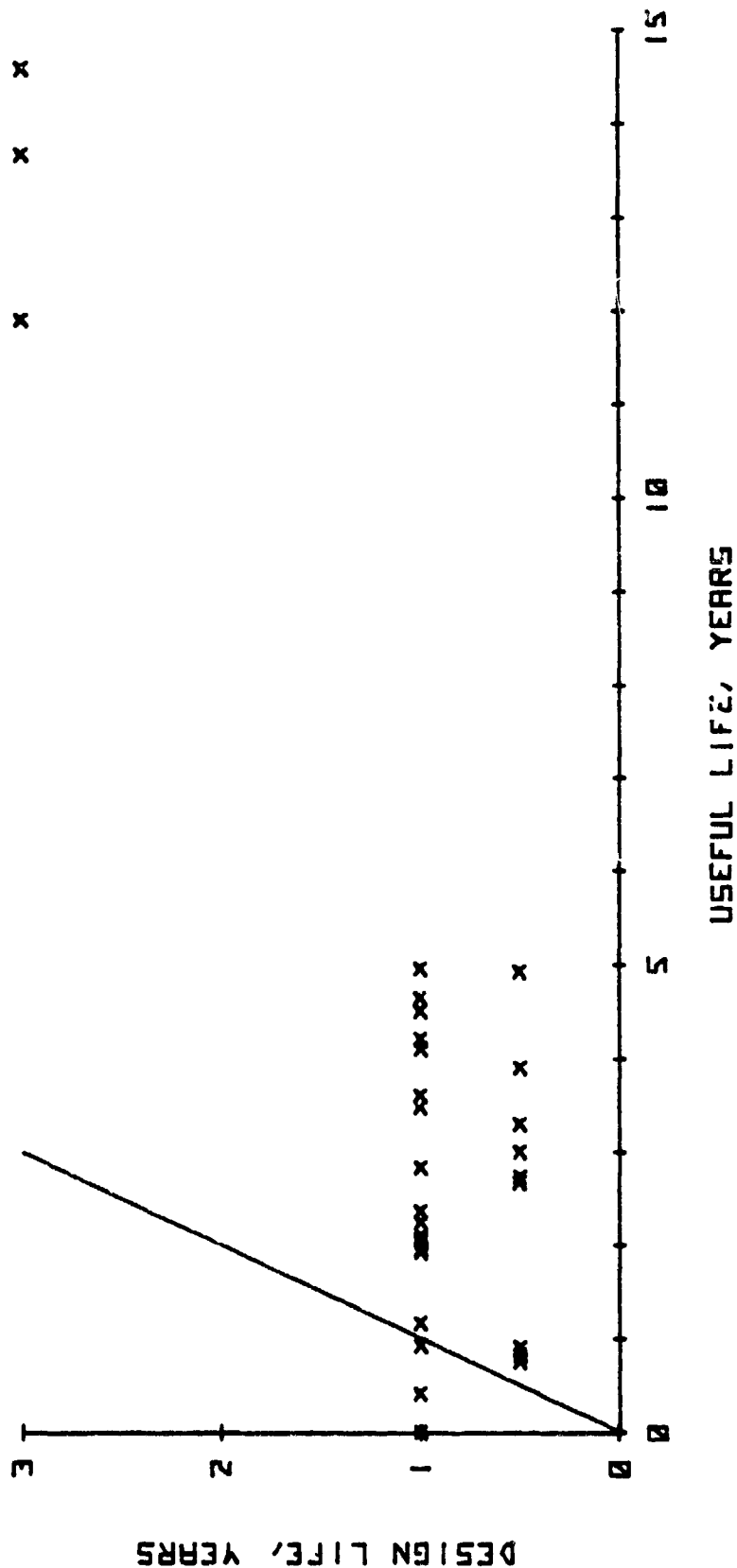


Figure 4. Comparison Between Design Life and Achieved Useful Life of Spacecraft Launched 1965 Through 1969

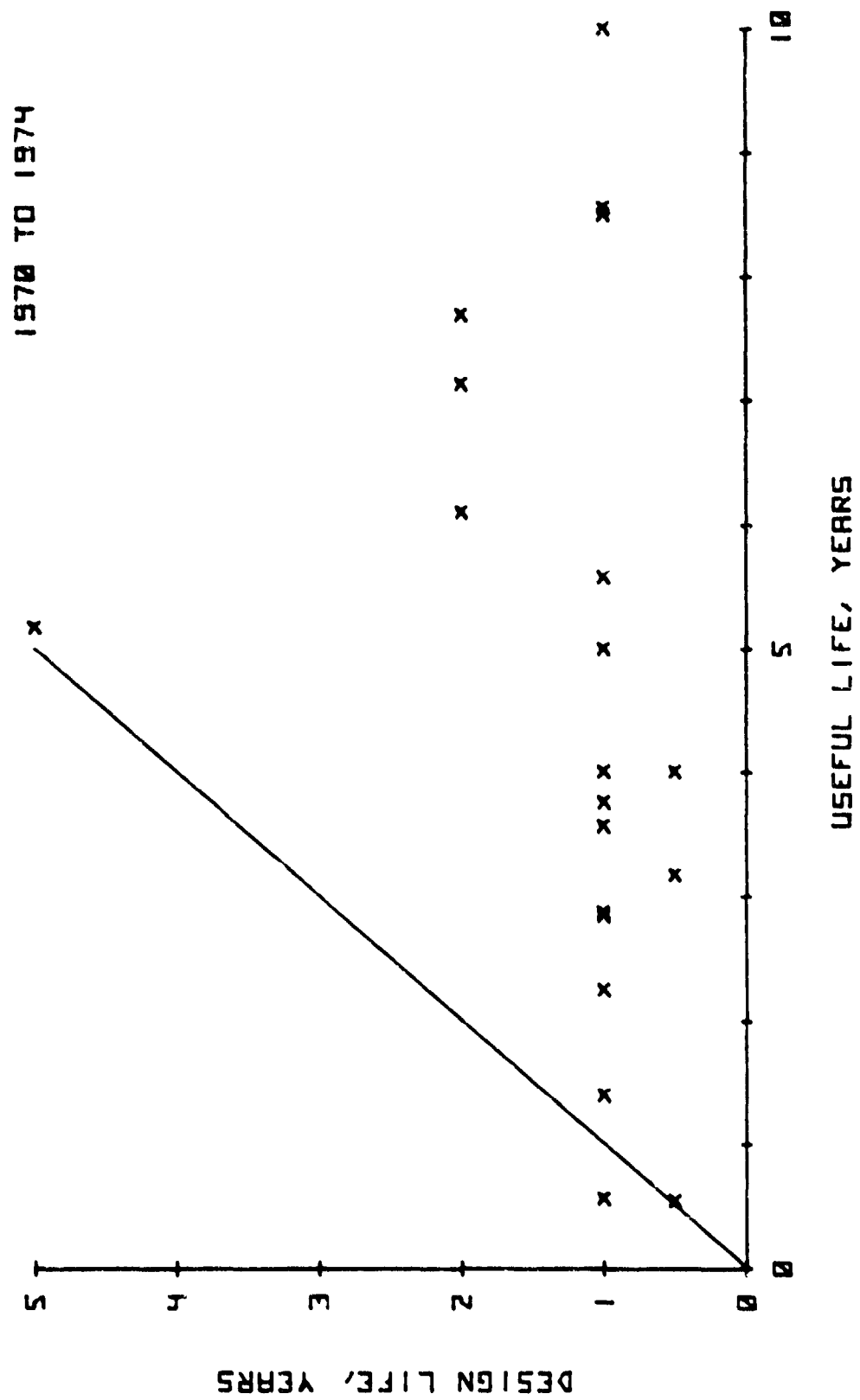


Figure 5. Comparison Between Design Life and Achieved Useful Life for Spacecraft Launched 1970 Through 1974

so designated failed to meet the goal, and in terms of median life were actually outperformed by the 6-month missions. In the 65-69 period, one-year mission lives were readily achieved with few exceptions, although the 6 month missions continued to perform as well as the one-year missions. The three-year missions (ATS 1, 3, 5) clearly outperformed the median lives of the shorter design goal spacecraft. In the 1970-74 period, although there is still considerable scatter in the data, a proportionality between design life and median useful life was beginning to develop, and continuation of the usual one-year goal had become a very conservative practice.

The fact that mission lives have tended to exceed design goals by a wide margin has long been recognized, and in the late seventies design goals for Goddard spacecraft began to routinely be extended to 2-5 years or more.

PROGRAM MATURITY AND TYPICAL LIFETIME

The majority of Goddard spacecraft have not been one-of-a-kind items, but have been members of a project series of largely identical spacecraft.

The most extensive program managed by Goddard has been the TIROS Project, consisting of four series of missions encompassing three generations of weather satellites with a total, to date, of 27 missions.

In examining lifetime data by series, two things become clear: first, that a "learning curve" often takes place over the first few missions, and second that each series seems to have a "normal" or "typical" lifespan. The major examples are shown in Table 2 below.

Table 2

PROJECT	NO. OF S/C TO REACH TYPICAL LIFESPAN	TYPICAL LIFESPAN (YRS)
TIROS	7	3-4
ITOS	3	3-4
OSO	3	3-4
OGO	3*	3-5
OAQ	2	8-10
NIMBUS	4	8-10

*Based on OGO I and II being classified as mission failures, despite long lifetimes.

The normal lifespan is essentially the wearout life of the mission. Some variability may be expected among projects as to what constitutes wearout, however. For example, a science mission returning unique data may be viable as long as one key experiment is active, whereas an applications satellite might be considered "worn out" at a much higher performance level.

As a matter of engineering interest, the major reasons for the relatively abbreviated earlier missions of each series are discussed below:

TIROS: The prime instruments on the TIROS missions were a pair of TV cameras, which were semi-redundant but had different viewing angles. Considerable difficulties were experienced with the shutters, focusing mechanisms, etc. of these cameras, as well as with tape recorders. The first six missions lost at least one camera in the first 90 days of flight.

ITOS: The first two flights of the second-generation TIROS experienced excessive brush wear and other problems in the momentum wheel assembly. This problem was solved on the third flight by a new design which featured a brushless motor.

OSO: Both OSO I and II lacked magnetic torquing capability, resulting in excessive use and premature depletion of control gas. OSO-I also lost its tape recorders early, and (through no fault of its own) was damaged by the "starfish" atmospheric radiation event.

OGO: OGO contained a number of deployable booms. One OGO-I boom did not fully deploy, creating an artificial horizon for the horizon sensor, and causing control gas to be rapidly depleted. Thus, three axis stabilization was not achieved, and the spacecraft had to be operated in a spinning mode, complicating data reduction. OGO-II's horizon sensors were sensitive to clouds, limiting their effectiveness, and again presenting an attitude control problem. Thermally induced boom bending caused attitude control problems on OGO-III as well, but the mission was officially successful.

OAQ: OAQ-I suffered a power failure which terminated the mission shortly after launch. A high-priority recovery effort was mounted, with the full resources of the Center being applied to the resolution of this and other OAQ problems. Subsequent missions were brought in-house for integration and test, rather than relying on the contractors facilities. The subsequent OAQ-II and OAQ-III missions were highly successful.

Nimbus: The Nimbus-I solar array drive failed after 26 days. Nimbus II and III both experienced ACS scanner failures short of 3 years in orbit. Having solved these problems, Nimbus IV achieved a 10 year useful lifetime, and subsequent Nimbuses appear headed for similar lifetimes.

Other Programs: Other programs have also shown growth in performance effectiveness over the first two or three launches, although not necessarily in a way which explicitly affected the duration of their useful lives. For example AE-C, the first of a three-mission sequence (not directly comparable to the much earlier AE-A and B missions) experienced a fortuitous situation when one memory programmer failed in the "read" mode and the redundant unit in the "write" mode, with little consequent effect on the mission. Trouble was also experienced with the S-Band Transponders, one of which became unstable with temperature, while the other became difficult to get into the high power mode. AE-D failed after about 6 months due to a single-point failure in the power system. The third mission, AE-E, on the other hand, was in excellent condition with no loss of redundancy or instruments when it reentered after 5 years in orbit on June 10, 1981.

TRENDS IN PROBABILITY OF SUCCESS

Growth in the probability of achieving successful operation for various durations ranging from 6 months to 5 years is shown in the family of curves in Figure 6. The curves are based on a moving average of 9 spacecraft, a sample size which was selected to optimize definition on the time axis while retaining a reasonable sample size. Note that the probability of achieving a useful lifetime of up to three years had reached an essentially stationary value by the late 1960's but that the probability of achieving even longer lifetimes appeared to be still growing as of 1975.

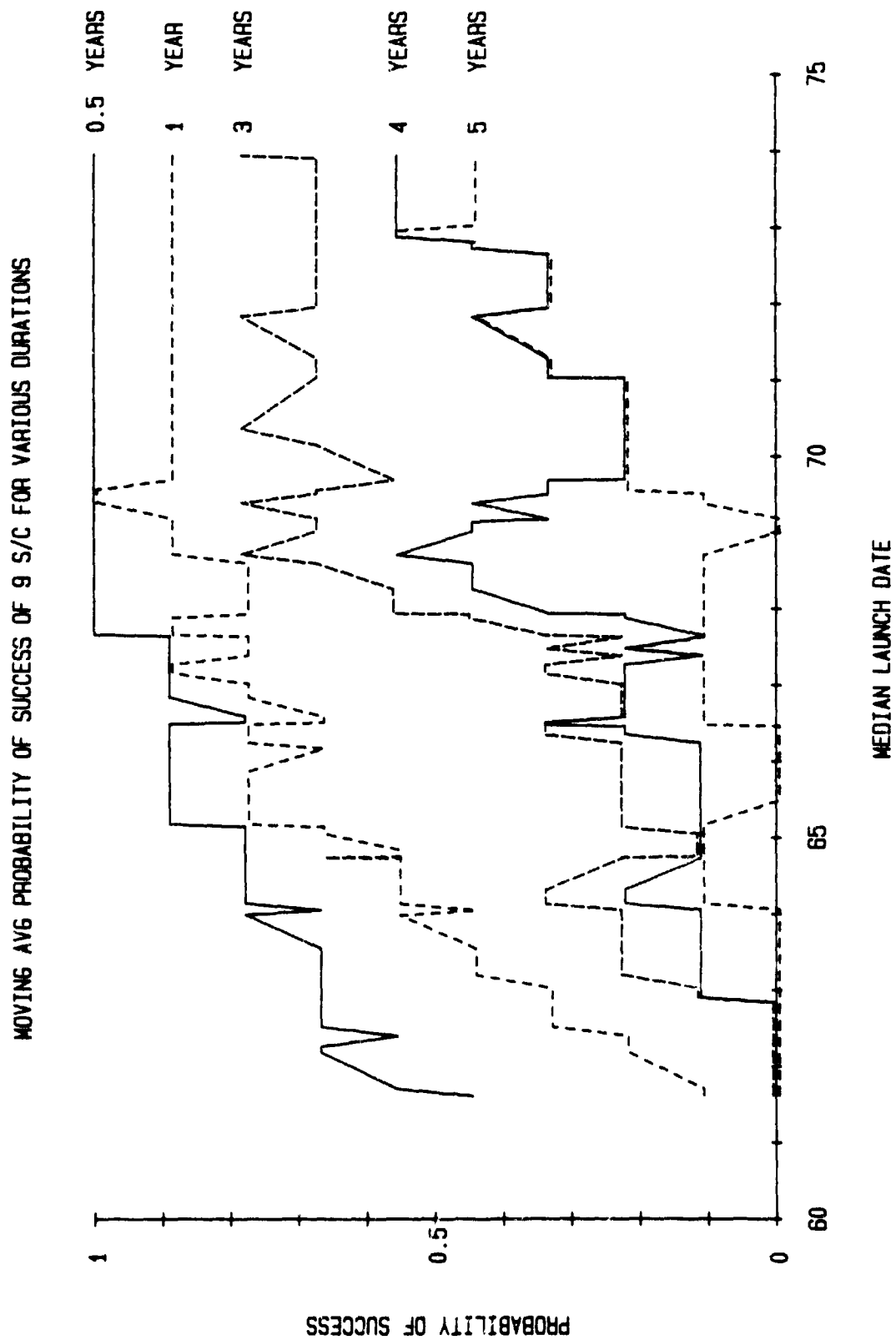


Figure 6. Probability of Achieving Various Useful Lifetimes as a Function of Launch Date

OPERATIONAL RELIABILITY: 1970-1980 Missions

Reliability is defined as the probability of achieving successful performance as a function of time. To denote that "successful performance" is defined specifically herein by useful lifetime, the modified term "operational reliability" will be used. Thus, a non-parametric (that is, independent of any assumed distribution) estimate of the operational reliability of the global population of spacecraft may be derived by dividing the number of units active at any given time by the number present in the original sample. In this case, the entire data base, including active projects, may be included in the sample by treating the active satellites as truncated data, that is, as data which ends before a conclusive result occurs. The truncation time for each active project was calculated as of July 1, 1981. This is dealt with by simply subtracting the truncated sample from both the numerator and denominator of the equation, yielding the overall expression:

$$R = \frac{N_O - N_F - N_T}{N_O - N_T} \quad (2)$$

Where: R = operational reliability
N_O = number in original sample
N_F = number "failed" (terminated)
N_T = number truncated

A historical view of the operational reliability curve at any point in calendar time covering the first five years of flight may be derived by taking a vertical slice through the data shown in the "probability of success" curve in Figure 6. However, it is of interest here to derive the curve from a larger sample, as well as to include the influence of the most recent missions.

Figure 7 illustrates the composite operational reliability of all Goddard spacecraft in the data base launched since 1970, based on equation 2. In addition to active spacecraft, Magsat was treated as truncated data on the grounds that it had not degraded between launch and the time it re-entered, as planned, six months later.

RELIABILITY MODELING

It is useful to derive a mathematical model to fit the observed data. This can be done by either a direct curve-fitting process or by utilizing the general expression for reliability:

COMPOSITE RELIABILITY: 1970-1980

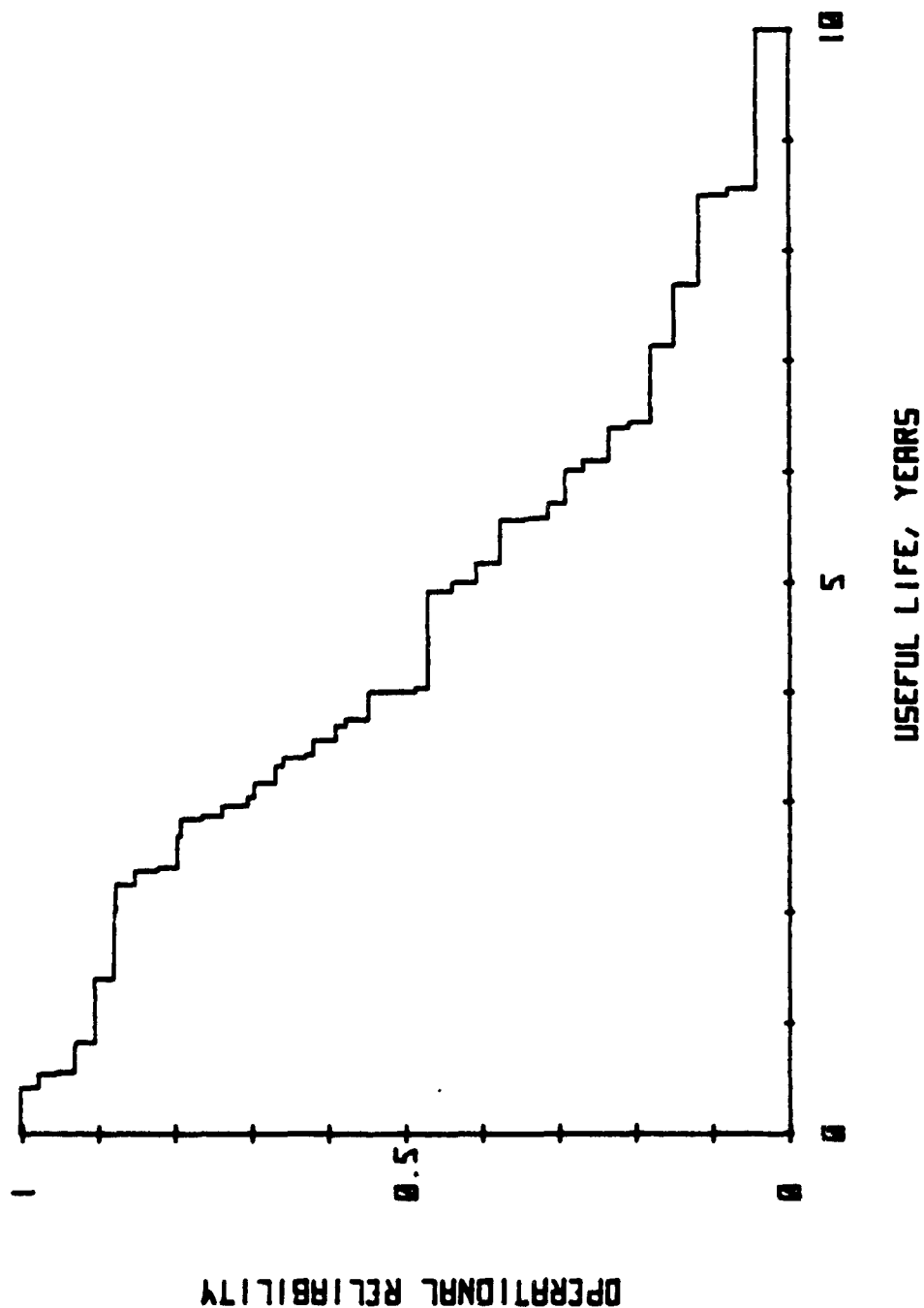


Figure 7. Operational Reliability for 43 Spacecraft Launched 1970 Through 1980

$$R = e^{-\int h(t) dt} \quad (3)$$

where $h(t)$, the hazard rate, or instantaneous failure rate, is defined as the probability of a failure occurring in an interval of time Δt as Δt approaches zero, given that the item has survived until the beginning of the interval. In reliability analysis, the most commonly used model is one in which the hazard rate is assumed to be constant, in which case the reliability expression reduces to:

$$R = e^{-\lambda t} \quad (4)$$

where λ is the failure rate.

The constant hazard rate model implies that the failures are chance occurrences which are independent of time. Hence, one would not expect this to be an appropriate model for spacecraft reliability, since many of the elements which limit spacecraft lifetime are clearly time-dependent (wearout, obsolescence, completion of mission, etc.) The poor fit of the constant failure rate model to the spacecraft data is illustrated in Figure 8.

Direct calculation of hazard rates is another approach to the development of a model. However, using the individual data points in these calculations results in too much scatter to be of value. Better results may be obtained by dividing the data into intervals and calculating the average values for each interval. Shooman (Reference 4) derives the following formula for determining the correct number of intervals:

$$K = 1 + 3.3 \log_{10} N \quad (5)$$

Where K is the optimum number of intervals and N is the number of failures. Since the data has 25 failure points (terminations), this suggests 5 or 6 intervals. Since the data covers 10 years, it is convenient to use five 2-year intervals. Ideally, the data should contain many more samples than those which failed, otherwise the sample size becomes too small to have any validity in the later intervals. Since this was unavoidable in the present case, which has only three data points in the last four years, the final two intervals were excluded, yielding the following result:

COMPOSITE RELIABILITY: 1970-1980

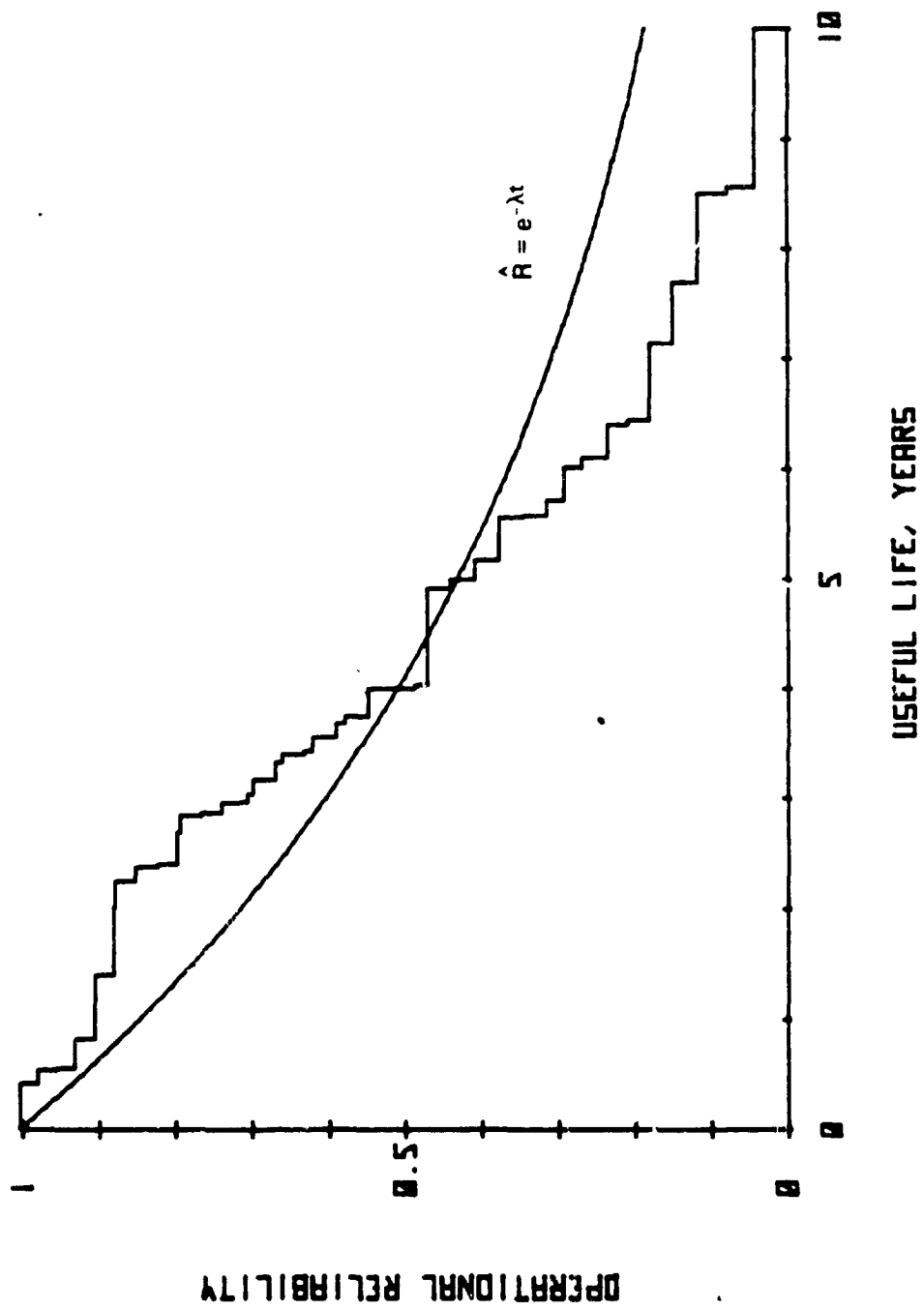


Figure 8. Constant Failure Rate Model

<u>Interval</u>	<u>Mid-point</u>	<u>$h(t)$</u>
0-2 years	1 year	0.06
2-4 years	3 years	0.19
4-6 years	5 years	0.27

Hence, the data shows an unquestionably increasing hazard rate, which is also virtually linear. Although it is obviously a questionable practice to fit a curve to only three data points, this illustrates both the method and the problems associated with using the hazard rate method. In this particular case, the best fit curve is the linear function:

$$\hat{h}(t) = 0.021 + 0.051t \quad (6)$$

Applying this to the generalized reliability equation (Equation 2) yields the model:

$$\hat{R} = \exp -[0.021t + 0.026t^2] \quad (7)$$

This curve is compared with empirical data in Figure 9. The fit is rather good, considering the uncertainty in the hazard rate function.

The most frequently used function in reliability modelling is the Weibull distribution, which is very flexible in its ability to fit many different curve shapes. In the simplified form applicable to reliability the equation is:

$$R = \exp - \left[\frac{t}{a} \right]^b \quad (8)$$

Where "b" and "a" are called the shape and scale parameters, respectively. A third parameter in the general Weibull expression called the location parameter is not required since R always equals one at $t = 0$. The Weibull fit to the present data yields the following expression:

$$\hat{R} = \exp - \left[\frac{t}{5.2} \right]^{1.9} \quad (9)$$

The resultant fit is shown in Figure 10. The hazard rate implied by this function is:

$$\hat{h}(t) = 0.37t^{0.9}$$

COMPOSITE RELIABILITY: 1970-1980

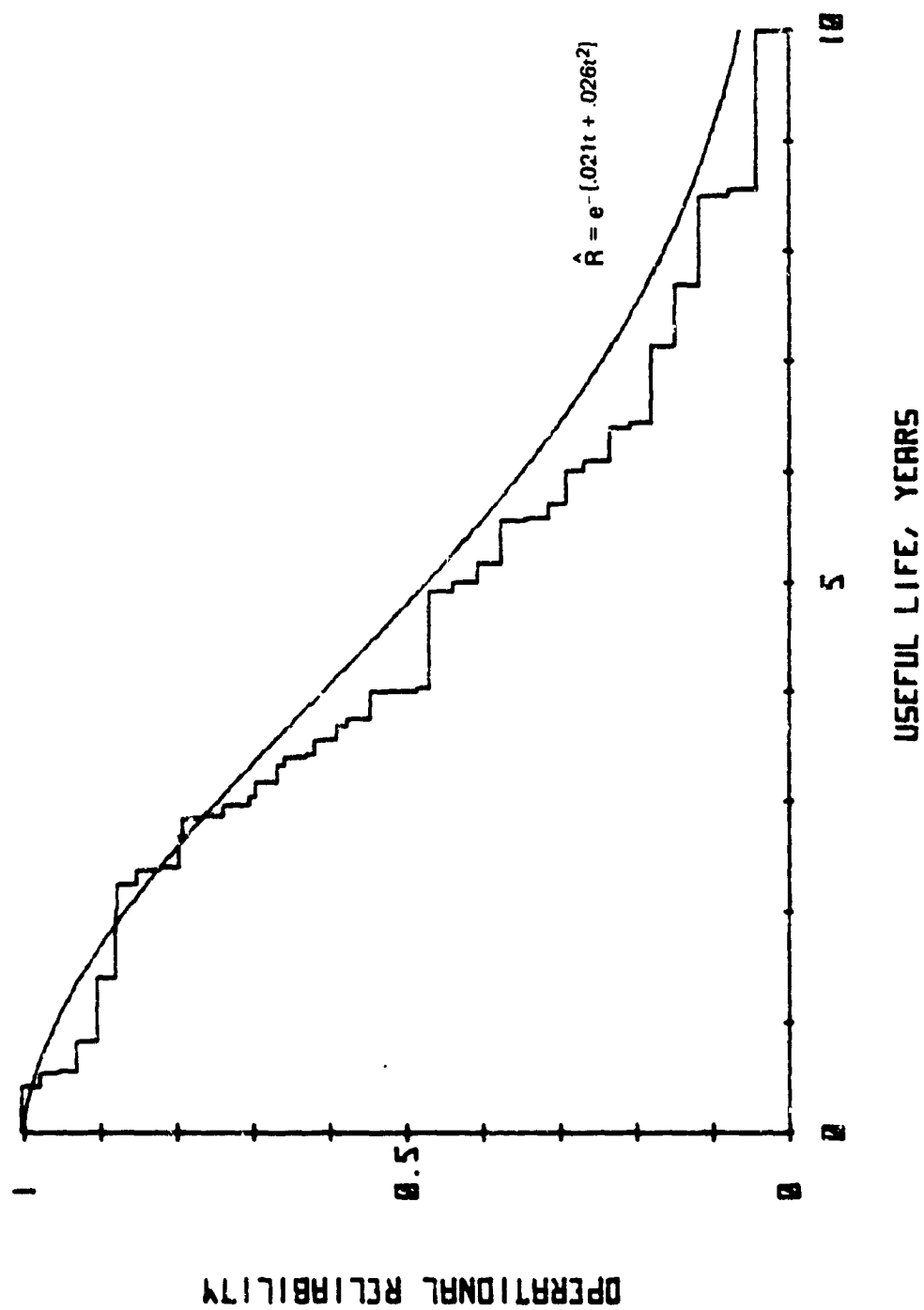


Figure 9. Hazard Rate Model

COMPOSITE RELIABILITY: 1970-1988

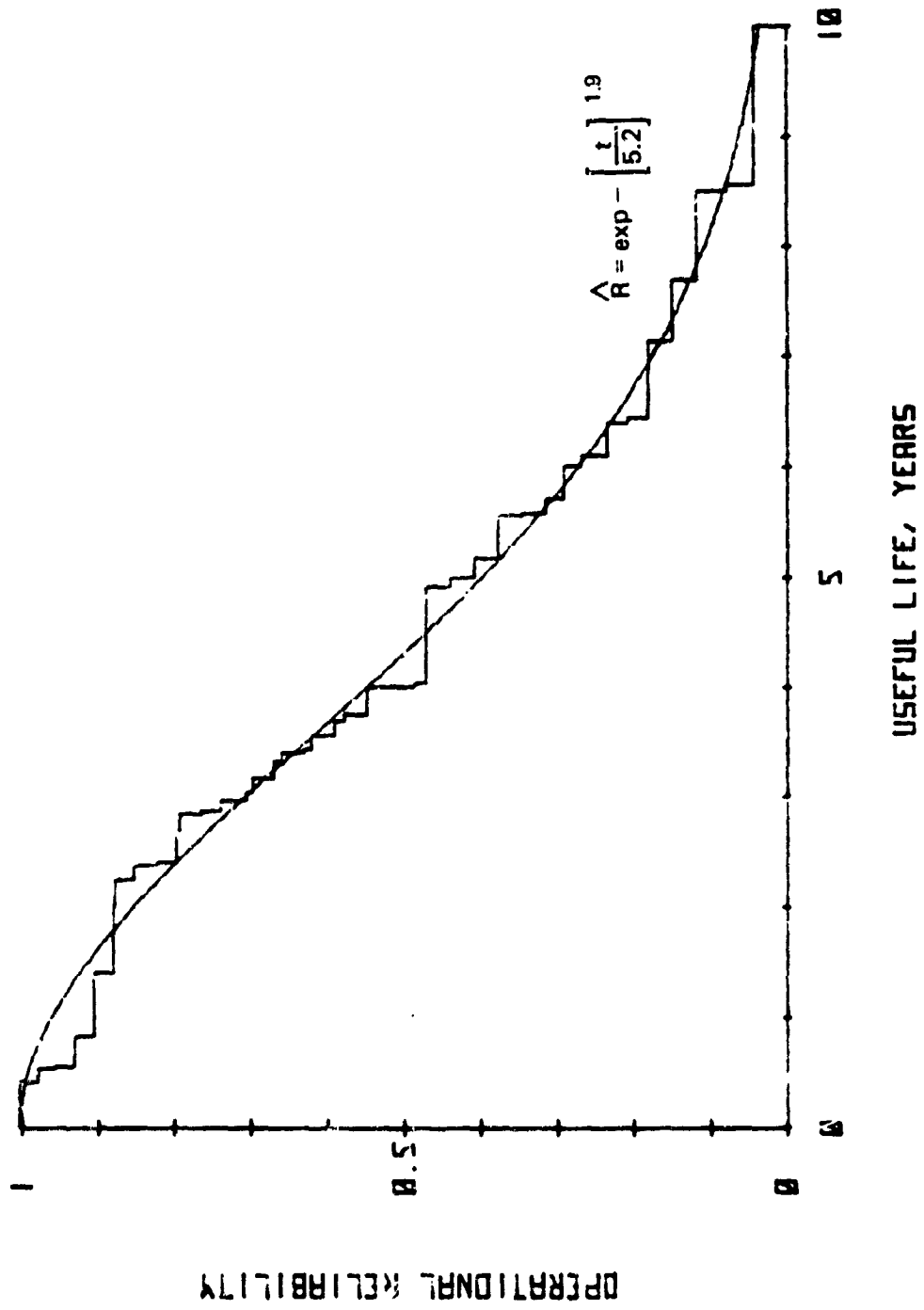


Figure 10. Weibull Model

Which is an increasing rate having a slightly decreasing slope. The slope change is virtually imperceptible over the period covered by the empirical data.

OPERATIONAL RELIABILITY OVER THE FIRST THREE YEARS OF FLIGHT

As illustrated in Figure 6, the probability of success, or operational reliability, has reached an essentially stationary value for at least the first three years of flight by 1970. Moreover, there is more homogeneity in spacecraft longevity data during the early portion of life, since some of the reasons that influence the decision to terminate a spacecraft in later periods, such as replacement or obsolescence, are not present. Also, the earlier stages of flight are obviously the most important, particularly the period encompassed by the design life, in evaluating the success of the program. Thus, it is of interest to investigate this period in more detail.

Figure 11 shows an expanded view of operational reliability for the first 3 years of flight with the specific mission terminations noted.

For the purposes of this report, the useful lifetime of SMM is considered to have terminated in December 1980, due to the loss of fine pointing control, although this is not necessarily an official viewpoint, and 2 of the 7 instruments are still receiving good data.

The reasons for termination of the missions with less than 3-year lifetimes are described and categorized below:

LESS THAN 1 YEAR

<u>SPACECRAFT</u>	<u>PRIMARY FAULT</u>	<u>PROBLEM CATEGORY</u>
SAS-B	Instrument Lost Power	Design
AE-D	S/C Lost Power	Design/Workmanship
SMM	Lost Fine Pointing Control	Design
ITOS-A	Momentum Wheel Failed	Design

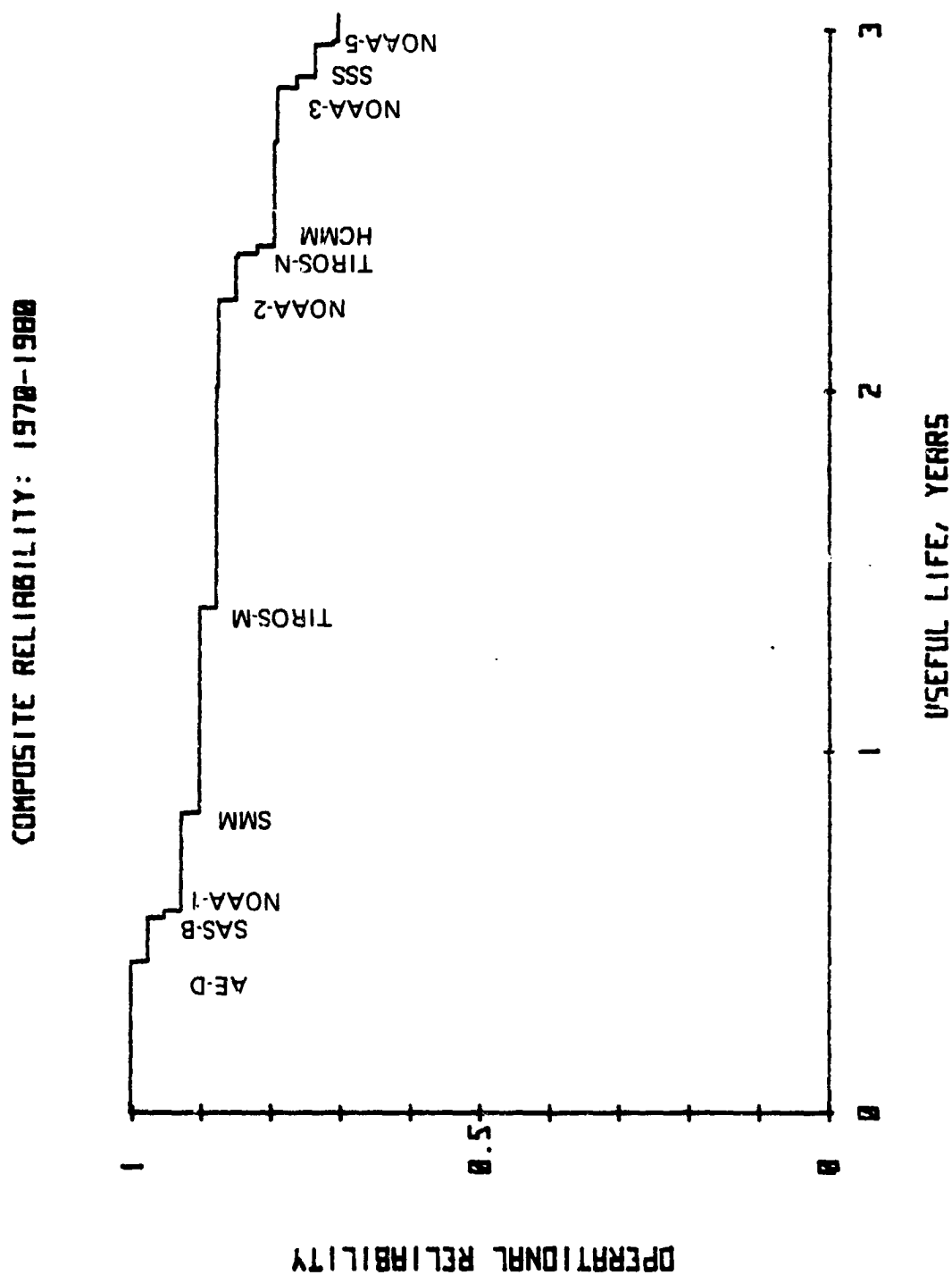


Figure 11. Operational Reliability Over the First Three Years of Flight for 43 Spacecraft Launched 1970 Through 1980 With Specific Terminations Noted

1-2 YRS (Exceeded Design Life)

TIROS-M	Momentum Wheel Degraded	Design
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2-3 YRS (Exceeded Design Life)

HCMM	Battery Degraded	Design/Quality
ITOS-D, F, H	Mechanical Degradation of Instruments	Design/Wearout
TIROS-N	Lost Both Inertial Measurement Units (IMU)	Unknown
SSS	Completed Mission	Wearout

Two of these missions, SSS and AEM-A (HCMM), were "low-cost" missions lacking box-level redundancy. SSS essentially completed its mission, and although the battery had failed as expected after slightly less than 1 year in orbit and the loss of the analog multiplexer (possibly due to a MOS damaged by radiation) after about a year and a half had caused some loss of analog data, the termination point just prior to three years was arbitrary and there would be substantial justification for treating this spacecraft as truncated data. HCMM experienced battery shorts attributed to cadmium migration, and required a superior effort in ground control to maintain it in active service after the first few months. Six of the others were missions of the TIROS Project, whose lives were limited primarily by wearout of mechanical devices, especially in the instruments.

Excluding the low-cost and TIROS/ITOS missions, only three missions failed to perform all mission-critical functions for at least three years, and each of these failed due to design problems occurring between 6 months and 1 year of flight. Further, all spacecraft which failed to achieve at least two years of useful life were the first or second of a series.

Evaluation of the foregoing must be tempered by the fact that an additional number of missions have been troubled by anomalies which threatened to curtail or very severely degrade their mission, although these problems did not necessarily shorten the useful lives of the spacecraft. A total of

nine such missions have been identified among the 1970-1980 flights, including one launch vehicle problem, of which only two are also included in the "less than three year life" category. Since this constitutes 20 percent of the total sample, it is important to keep this in mind in evaluating spacecraft reliability. The missions and specific problems they encountered are described in Appendix C.

OTHER STUDIES

Extensive related studies were conducted during the mid-seventies by Rand, TRW, Aerospace Corporation and possibly others. The findings of these studies, which were not limited to Goddard or NASA projects, are of general interest.

The Rand study (Ref. 1) was aimed at aiding the Air Force in determining procurement strategies for long-term missions. The report states "At the start of the study we felt that there should be a number of instinctively plausible relations between various spacecraft parameters and spacecraft reliability . . . No truly significant correlations were found . . ."

The attempted correlations were between achieved lifetime and design life, program costs, and percentage of program costs allocated to reliability. No attempt was made to normalize the data or investigate the parameters discussed herein. The major positive finding seemed to be that reliability models built up from empirical component failure rate data should be less pessimistic and therefore more accurate than those built up from exponential piece-part failure rates.

The referenced TRW report (Reference 2) was one of a series representing a long term effort by TRW to understand and improve reliability modelling techniques. TRW found that there are good programs and problem programs, with reliability modelling having generally been very pessimistic in forecasting operational reliability overall, but systematically optimistic in predicting the reliability of problem programs. The author believed but had not proven a correlation between program funding problems (overruns, etc.) and the likelihood of the program becoming a problem program. Oddly, a review of the TRW data shows that the problem programs tended to be those

with the longest assigned design lives, resulting in a negative correlation between design life and achieved life.

Ten TRW spacecraft, or 24% of those launched, had catastrophic or near-catastrophic design failures (not necessarily within the design life), all but one of which were single-point failures. TRW did note a positive effect from program maturity, but this apparently manifested itself as a lower incidence of failures in components rather than in longer achieved lifetimes. By contrast, the Goddard data shows no generic problems in mission series that did not yield to design improvement in subsequent missions.

The Aerospace study (Ref. 3) was aimed primarily at program management strategy for cost reduction, and was performed for NASA Headquarters. It included data from seven Goddard spacecraft in its data base. A feature of this study was an ambitious attempt to quantify mission complexity by assigning weights to 20 different parameters. The study evaluated various parameters against "program success" (not reliability) defined as a combination of cost and schedule control and mission performance factors. Mission performance was based entirely on anomalies occurring during the first 30 days of flight. The rationale for this performance criterion was that the major design defects would probably appear within this interval. In evaluating their results, it should be noted that the Goddard data shows that since 1970 the most damaging defects have taken six months to one year to manifest themselves.

Under the ground rules of the study, it was concluded that neither program cost nor complexity are correlated with mission success. On the other hand, freedom from hardware defects correlated well with the percentage of program cost spent on production quality assurance (but not for development quality assurance although the data seems insufficient in this regard), and very strongly with test program thoroughness in general and flight acceptance testing in particular.

The data is presented graphically, with the project name noted at each data point. It is interesting to note that the NASA programs, most of which were Goddard projects, were clearly superior in

this regard, having consistently had more thorough test programs and correspondingly fewer flight defects. Further, Goddard's Q.A. programs were consistently less costly while at the same time more effective than others in the study.

The Rand study reported operational reliability data, which was fitted to a Weibull distribution, and quoted the TRW data, similarly fitted. The reported best-fit curves were:

$$\text{TRW: } R = \exp - \left[\frac{t}{117} \right]^{0.911} \quad ; \quad \text{Rand: } R = \exp - \left[\frac{t}{232} \right]^{0.859}$$

Where t is in months.

The resultant reliability at 1, 2, and 3 years, as compared with the Goddard data, is as follows:

<u>RELIABILITY ESTIMATE</u>			
<u>TIME</u>	<u>RAND</u>	<u>TRW</u>	<u>GSFC</u>
1 YR	.924	.882	.956
2 YR	.867	.790	.869
3 YR	.817	.710	.752

The Rand study included twenty-two Goddard spacecraft in a total of 73 missions. The TRW study included the six OGO missions in a total of 42 missions. The Aerospace study contained only 14 spacecraft, of which 7 were Goddard missions.

DISCUSSION

The general findings of the study are:

... Median spacecraft useful lifetime grew at the persistent and essentially linear rate of about a third of a year per year through at least 1974. More recent data is indeterminant since the majority of more recent missions are still active, but the 1975 median has already reached the predicted value, and there is no reason to believe that the trend is not continuing. If so, the median lifetime

of spacecraft launched today would be about 7½ years. The normal wearout lifetime of many configurations might reasonably be expected to be considerably longer. In the future, however, composite data may become less meaningful as greater correlation between design life and useful life is attained, and missions become increasingly tailored to specific lifetime goals.

2. By 1970, operational reliability had become an essentially stationary function over the first three years of flight, although longer-term reliability was still growing as of at least 1975. The four missions of the 1970-1980 composite sample of 42 spacecraft (excluding Magsat) which failed to survive the first year in orbit were scattered through the decade, further substantiating the assumption that no further improvement is imminent. The failures in each case were attributable to systematic (rather than random) causes linked to design weaknesses. In addition, about 20% of all spacecraft experienced launch phase or early orbit anomalies which threatened to curtail or seriously degrade the mission. The majority of these difficulties were also attributable to systematic causes.

3. Each project seems to have a normal lifetime which is not correlated with its design life except in the sense that it exceeds it by a wide margin, and in the sense that by the early 1970's the beginning of a trend toward missions with longer design goals achieving longer median useful lifetimes could be observed. The normal lifetime of a mission seems to be a function of the particular configuration employed, which determines the wearout life of the critical components, and the termination criteria applied to the specific mission. Often this normal lifetime is either not achieved until the third spacecraft of a series, or lower-quality performance is tolerated on the earlier missions.

4. By inference, then, random failures seem to have played a relatively minor role in establishing useful lifetimes, although they undoubtedly have made an indeterminate contribution to the degradation which is often a key factor in the decision to terminate a mission. A probable reason for

the relatively minor impact of random failures is that processes such as quality assurance, testing, and especially the use of redundancy are more effective against these defects than they are against design problems.

5. Although not specifically investigated in the current study, the findings of the referenced related studies to the effect that no correlation has been found between mission cost and complexity is qualitatively corroborated by this study in that the missions which had relatively short lives do not fit any particular pattern in this regard. They range from the highly sophisticated SMM spacecraft to the low-cost SSS and HCMM programs. On reflection, it might be said that this lack of correlation is, in a sense, almost an Agency goal. Low cost missions for example are invariably less complex, and are much more likely to be designated "high risk" than others. Thus, it should not be surprising that the higher risk assumed on these missions is counterbalanced by the greater complexity of the higher cost missions in terms of the probability of early failure. Although not explicitly explored in this report, there does seem to be a gross correlation between normal lifetime and cost/complexity level, possibly because redundancy, for example, while not a good defense against design problems, does tend to extend wearout lives by providing a backup for the failed unit. There is some question as to whether finer-grained correlations are feasible because of the difficulty of quantifying complexity and acquiring cost data which is directly comparable on a mission-to-mission basis.

The agreement in the early life reliability calculations between the Goddard data and the broader-based TRW and Rand data is close enough that no statistical significance may be inferred regarding the differences. It is noted however, that the Rand and TRW Weibull models both call for an exponent (shape factor) of less than one, which corresponds to a declining hazard rate. (A shape factor of one corresponds to a constant failure rate). Although in-orbit anomaly studies at Goddard and elsewhere have shown that failure rates of components tend to decline as a function of time, it does not follow that spacecraft failure rates should also decline. They depend, in part, on the

cumulative effect of component failures, which can only increase with time regardless of the shape of the component failure rate curve. Since the other factors contributing to spacecraft termination are also increasing functions of time (obsolescence, replacement, withdrawal of funding, etc), it is difficult to envision a scenario in which a decreasing hazard rate would be appropriate. The Goddard data clearly shows an increasing hazard rate, as might reasonably be expected.

In any case, the models are not considered directly applicable to predicting the reliability of any arbitrary future spacecraft, which might better be done by making allowance for the position of the spacecraft in its series, and estimating the normal lifetime of the series either by direct comparison with similar series or by generalizing from extrapolated life data. The primary value of the model is to allow quantitative comparison with future data as a means to evaluate progress.

The study clearly shows that the most fruitful path to improved reliability lies in reducing the probability of unexpected design problems. It is by no means clear, however, how this might be accomplished. The independent design review function in use at Goddard effectively brings to bear the cumulative experience of Center experts on each spacecraft, and is informally credited with averting many potential difficulties. Suggestions such as better end-to-end testing and more realistic test parameters seem facile in that they beg the question of how these goals are to be achieved, let alone in a cost-effective manner. A complicating element is the fact that the catastrophic failures in Goddard spacecraft have taken 6 months or more to materialize, and hence would have required impractically long life tests, or life tests accelerated in some indeterminate fashion, to accomplish.

More imaginative approaches were proposed by Barnett (ref 2), but they seem impractical. One was to consider design redundancy, by which is meant the concurrent use of redundant components of different design developed by different groups. The other was to expand the FMEA procedure to include questioning the design itself (i.e., what if this design just plain does not work), a procedure which seems too open-ended to be "do-able".

The advent of Shuttle provides an interesting situation which in a sense may render the question moot. If the first Shuttle flight of a given project is considered the ultimate life test, and design problems continue to be solvable for subsequent missions, the problem will in effect be solved at a cost which is the cost of retrieval and refurbishment multiplied by the fraction of spacecraft which experience these problems.

It need hardly be said that the emphasis on design and systematic failure throughout this report should in no way be construed to imply that the flight assurance activities in force at Goddard are either entirely efficient and cost-effective at eliminating random defects on the one hand or that such defects are trivial on the other. The growth in spacecraft reliability has been achieved in part by technological advances in the design of aerospace equipment for longer lifetimes, and in part in spite of the increasing complexity and constant need to deal with unproven hardware brought about by these same advances. These developments present a constant challenge to develop increasingly perceptive screening techniques simply to maintain equivalent failure rates.

It should also be clear that operational reliability is only a partial measure of total performance, which also involves the quality and quantity of scientific data produced during the life of the mission. This in turn is affected at least subtly by all but the most trivial anomalies, whether random or systematic. Substantial further study is needed to develop models which incorporate all aspects of mission performance in a unified expression, and to measure the effectiveness and importance of all phases of the flight assurance program.

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1. "Rand Spacecraft Acquisition Study: A Briefing" Bruno W. Augenstein, WN-9551-PR, August 1976
2. "Demonstrated Orbital Reliability of TRW Spacecraft" F. Barnett, TRW publication 74-2286.142, December 1974
3. Standardization and Program Practices Analysis: Final Report, Aerospace Report No. ATR-78 (7659)-1, 5 Dec 1976
4. Probabilistic Reliability: An Engineering Approach, M.L. Shooman, Mc Graw Hill, Inc. 1968

APPENDIX A
SPACECRAFT LIFETIMES

SPACECRAFT LIFETIMES

SPACECRAFT	LAUNCH DATE	DESIGN LIFE	USEFUL LIFE	ACTIVE LIFE	SOURCE	REMARKS
TIROS-I	4/1/60	0.25	.24	.24	1	TV system useful for 77 days
Explorer VIII (S-30)	11/3/60		.15	.15	6	Last transmiss.on 12/28/70
TIROS II	11/23/60	0.25	.63	1.03	2	TV data useful to 7/12/61
Explorer XI (S-15)	4/27/61		.61	.61	7	Last transmission 12/7/61
TIROS-III	7/12/61	0.25	.40	.63	2	TV data useful to 12/4/61. Lost tape recorders
Explorer XII (S-3)	8/14/61	1.00	.31	.31	5	Transmission ceased abruptly
TIROS IV	2/6/62	0.25	.36	.44	1	TV useful to 6/9/62. Lost tape recorders
OSO-I	3/7/62	0.50	1.40	1.40	3	Lost tape recorder @ 2 mos. Starfish incident degraded power system
Ariel-I (S-51)	4/26/62	1.00	0.88	0.88	5	Degraded by starfish incident of 7/9/62
TIROS V	6/9/62	0.50	0.88	0.88	1	TV useful to 5/4/63. Camera filaments failed
TIROS VI	9/12/62	0.50	1.06	1.06	1	TV useful to 10/11/63. Filaments and focus out
Explorer XIV (S-3a)	10/2/62		0.85	1.20	5	Last transmission, 2/17/64
Explorer XV (S-3b)	10/27/62	0.17	0.26	0.55	5	Despin system failed. Last transmission 5/19/63
Relay I	12/13/62	2.00	2.53	2.53	6	Lost power, mission failure
Syncom I	2/14/63	2.00	0	0	7	
Explorer XVII (S-6)	4/3/63	0.25	.27	.27	5	Batteries degraded. No solar array
TIROS-VII	6/19/63	0.50	4.33	4.96	1	Deactivated. Camera focus out 12/65
IMP-A	11/26/63	1.00	0.82		5	
TIROS VIII	12/21/63	0.50	3.53	3.53	1	Deactivated
Relay-II	1/21/64	1.00	1.68	3.50	6	
Ariel-II (S-52)	3/27/64	1.00	0.53		5	Had spin rate and attitude control problems

SPACECRAFT LIFETIMES

SPACECRAFT	LAUNCH DATE	DESIGN LIFE	USEFUL LIFE	ACTIVE LIFE	SOURCE	REMARKS
Explorer XX (S-48)	8/25/64		1.60	1.60	7	Based on last transmission 3/30/66
Nimbus-I	8/28/64	0.50	0.07	0.07	5	Solar array drive failed.
OGO-I (A)	9/4/64	1.00	5.23	5.23	4	Mission failure. 3-axis stabilization not achieved
IMP-B	10/21/64	1.00	0.50	1.25	5	Reentered. Placed in wrong orbit.
Explorer XXVI (S-3c)	12/21/64	1.00	2.10	2.10	5	Last transmission 1/21/67
TIROS-IX	1/22/65	0.5	2.73	3.4	1	Deactivated. Camera contrast out 10/66
OSO-II	2/3/65	0.5	0.75	0.75	3	Used up control gas
IMP-C	5/29/65	1.0	1.92	1.92	5	Reentered. Source #6 quotes 300 days (0.82 yrs)
TIROS-X	7/2/65	1.0	1.16	2.00	1	Deactivated
OGO-II (C)	10/14/65	1.0	3.48		4	Mission failure: Horizon scanners did not maintain earth lock
ESSA-I	2/3/66	1.0	2.36	2.36	1	Deactivated
ESSA-II	2/28/66	1.0	4.64	4.64	1	Deactivated
OAO-I	4/8/66	1.0	0	0	5	Mission failure: Lost power
Nimbus-II	5/16/66	0.5	2.67	2.67	5	ACS scanner failed
AE-B	5/25/66	0.5	0.82		5	Higher than planned orbit. Two sensors did not work
OGO III (B)	6/6/66	1.0	2.04	3.5	4	Boom oscillation problem
AIMP-D	7/1/66	0.5	4.92		13	Failed to achieve lunar orbit
ESSA-III	10/2/66	1.0	2.02	2.02	1	Deactivated. Cameras failed
ATS-I	12/6/66	3.0	ACTIVE	ACTIVE		Gas expended
ESSA-IV	1/26/67	1.0	0.41	1.27	1	Deactivated. One camera failed, one degraded.
OSO-III	3/8/67	0.5	3.0	3.0	15	Tape recorder failure at 18 mos.
ESSA-V	4/20/67	1.0	2.83	2.83	1	ACS controlled manually
IMP-F	5/24/67	1.0	1.95	1.95	10	Deactivated. IR failed, cameras gradually degraded
AIMP-E	7/19/67		3.50	3.50	13	Reentered
OGO-IV (D)	7/28/67	1.0	2.24	2.75	4	Lunar orbit. Subsequent period of intermittent operation
						Thermal bending of antenna caused stabilization control problem

SPACECRAFT LIFETIMES

SPACECRAFT	LAUNCH DATE	DESIGN LIFE	USEFUL LIFE	ACTIVE LIFE	SOURCE	REMARKS
OSO-IV	10/18/67	0.5	0.90	ACTIVE	15	Tape recorder failure at 6 mos
ATS-III	11/5/67	3.0	ACTIVE	ACTIVE	--	Instruments no longer in use
ESSA-VI	11/10/67	1.0	2.09	2.09	1	Deactivated. Cameras degraded
OGO-V (E)	3/4/66	1.0	3.60	3.60	4	Deactivated. Data glut
RAE-A	7/4/68	1.0	4.50	4.50	9	Deactivated. Data quality had become marginal
ESSA-VII	8/16/68	1.0	0.92	1.56	1	Deactivated. Early camera and tape recorder failures
QAO II	12/7/68	1.0	4.20	4.20	12	Prime instrument (WEP) failed.
ESSA-VIII	12/15/68	1.0	4.95	6.75	1	Deactivated. Camera problems
OSO-V	1/22/69	0.5	3.9	3.9	15	Deactivated. Standby after 4/71
ESSA-IX	2/26/69	0.5	4.1	4.1	1	ACS Scanner failed 1/72
Nimbus III	4/19/69	1.0	2.67	2.25	15	Deactivated. Data glut
OGO-6 (F)	6/5/69	1.0	2.06	3.51	4	Reentered
IMP C	6/21/69	0.5	3.51	3.30	13	Mission officially unsuccessful.
OSO-VI	8/9/69	0.5	3.30	ACTIVE	15	Stabilization not achieved.
AT V	8/12/69	3.0	ACTIVE	ACTIVE	--	Momentum wheel assembly failed
TIROS-M	1/23/70	1.0	1.40	1.40	15	Deactivated
Nimbus-IV	4/8/70	1.0	10.00	10.00	15	Deactivated. Momentum wheel assembly problems
NOAA-1 (ITOS-A)	12/11/70	1.0	0.56	0.75	15	Transmitter failure terminated mission
SAS-A	12/12/70	0.5	4.00	4.00	15	Reentered
IMP-I	3/13/71	1.0	3.56	3.56		Reentered due to bad orbit
OSO-VII	9/29/71	0.5	3.17	3.17		Deactivated. Battery unusable, as expected after 1 year
SSS-A	11/15/71	1.0	2.87	2.87		Deactivated: Funding withdrawn
Landat-1 (ERTS-A)	7/23/72	1.0	5.58	5.58	15	Reactivated: Funding withdrawn
OAO-C	8/21/72	1.0	8.50	8.50		Power system failure terminated mission
IMP-H	9/22/72	2.0	6.10	6.10	15	Standby after 3/74. Some experiments failed.
NOAA-2 (ITOS-D)	10/15/72	1.0	2.25	2.40		

SPACECRAFT LIFETIMES

SPACECRAFT	LAUNCH DATE	DESIGN LIFE	USEFUL LIFE	ACTIVE LIFE	SOURCE	REMARKS
SAS-B	11/16/72	0.5	.54	.54		Experiment low voltage power supply failed.
Nimbus-5	12/12/72	1.0	ACTIVE	ACTIVE		Deactivated. Mission objectives achieved.
RAE-B	6/10/73	1.0	3.75	3.75		All instruments operating.
IMP VIII (J)	10/25/73	2.0	ACTIVE	ACTIVE		Deactivated. Radiometer, VTPR, VHR out
NOAA-3 (ITOS-F)	11/6/73	1.0	2.84	2.84		Reentered
AE-C	12/16/73	1.0	5.00	5.00		VISSR degraded after 1 month.
SMS-1	5/17/74	2.0	ACTIVE	ACTIVE	14	Standby since 1/76
ATS-6 (F)	5/30/74	5.0	5.17	5.17		Deactivated.
NOAA-4 (ITOS-G)	11/15/74	1.0	4.00	4.00		Deactivated. Radiometer, VHR's out
Landsat-2	1/22/75	1.0	ACTIVE	ACTIVE		Yaw flywheel stopped 11/79, re-covered 5/80
SMS-2 (B)	2/6/75	2.0	ACTIVE	ACTIVE	14	Standby from 4/78 to 4/79
SAS-C	5/7/75	1.0	4.92	4.92		Reentered.
Nimbus-6 (F)	6/12/75	1.0	ACTIVE	ACTIVE		Tape recorders have failed.
OSO-8 (I)	6/2/75	1.0	3.40	3.40	15	Funding withdrawn
AE-D	10/6/75	1.0	0.42	0.42	15	Shorted diode in power supply electronics
GOES-1 (A)	10/16/75	3.0	ACTIVE	ACTIVE	14	Standby since 11/79 VISSR degraded 3/79
AE-E	11/20/75	1.0	5.56	5.56		Reentered 6/10/81
NOAA-5 (ITOS-H)	7/29/76	1.0	2.96	2.96		Failed 7/79
GOES-2 (B)	6/16/77	3.0	ACTIVE	ACTIVE	14	VISSR failed 1/79
ISEE-A	10/22/77	2.0	ACTIVE	ACTIVE		Some instrument losses
IUE	1/26/78	3.0	ACTIVE	ACTIVE		Fully operational. Some problems with computer "HALTS"
Landsat-C	3/5/78	3.0	ACTIVE	ACTIVE		Problems with MSS instrument
AEM-A (HCMM)	4/26/78	1.0	2.40	2.40		Deactivated. Battery degraded
GOES-3 (C)	6/16/78	3.0	ACTIVE	ACTIVE	14	VISSR degraded 9/80
ISEE-C	7/12/78	2.0	ACTIVE	ACTIVE		Some instrument losses

SPACECRAFT LIFETIMES

SPACECRAFT	LAUNCH DATE	DESIGN LIFE	USEFUL LIFE	ACTIVE LIFE	SOURCE	REMARKS
TIROS-N Nimbus-7 (G)	10/13/78 10/24/78	2.0 1.0	2.38 ACTIVE	2.38 ACTIVE		ACS failed 2/27/81 Solar array power and some instruments degraded Battery degraded Fully operational Reentered as planned Lost fine pointing control 12/12/80 Some loss of redundancy
AEM-B (SAGE) NOAA-6 (A) Magsat SMM GOES-D	2/18/79 6/27/79 10/30/79 2/14/80 9/9/80	1.0 2.0 0.4 2.0 3.0	ACTIVE ACTIVE 0.50 0.83 ACTIVE	ACTIVE ACTIVE 0.50 ACTIVE ACTIVE	14	

DATA SOURCES

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9. Radio Astronomy Explorer-B, June 1973 (GSFC press release)
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11. Project Development Plan: Orbiting Solar Observatories (OSO), Rev. 5
12. OAO-2 Final Flight Evaluation Report, Grumman Aerospace Corp. July 1973
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14. SMS/GOES monthly and yearly reports
15. Compiled History of Parts Quality and Flight Experience as of April 1, 1979 (Mackenzie: Vugraphs)
16. Interplanetary Monitoring Platform IMP-J (GSFC)

APPENDIX B
LAUNCH VEHICLE PERFORMANCE

APPENDIX B

Launch Vehicle Performance

The following Goddard Missions were unsuccessful due to launch vehicle failure:

<u>Mission</u>	<u>Launch Date</u>	<u>Launch Vehicle</u>
ECHO V	5/13/60	DELTA
PIONEER P-30	9/25/60	ATLAS ABLE
PIONEER P-31	12/15/60	ATLAS ABLE
BEACON A (S-66)	3/19/64	DELTA
IMP-B	10/4/64	DELTA
OSO-C (S-57)	8/25/65	DELTA
ATS-II	4/6/67	ATLAS AGENA
NIMBUS-B	5/18/68	THORAD AGENDA D
ATS-IV	8/10/68	ATLAS CENTAUR
OAQ-B	11/30/70	ATLAS CENTAUR
ITOS-B	10/21/71	DELTA
ITOS-E	7/16/73	DELTA
NOAA-B	5/29/81	ATLAS-F

Recent reliability figures for the most frequently used NASA launch vehicles are:

	<u>LAST 10 LAUNCHES</u>	<u>LAST 20 LAUNCHES</u>
SCOUT	0.90	0.95
DELTA	1.00	1.00
CENTAUR	1.00	0.95

APPENDIX C
SERIOUS EARLY ORBIT ANOMALIES

APPENDIX C

SERIOUS EARLY ORBIT ANOMALIES

SSS: This spacecraft had 2 long and 2 short booms. Active nutation damping had been considered, but was deemed unnecessary. After orbital injection, a high nutation rate was observed. It was felt that this was produced by tipoff, and would soon damp out. Instead, the nutation angle continued to increase, threatening to put the spacecraft in a tumbling mode.

At this point, an ingenious plan was devised to utilize the magnetic attitude coil in an unplanned mode to introduce damping. This required reprogramming the on-board computer to pulse the coils. The technique worked and the mission was saved. The problem was attributed to thermal distortion of the booms which induced oscillations and changed the system's mass properties. The lesson learned was subsequently applied to the 750 foot booms utilized on the RAE missions, which were perforated to allow more even solar heating.

ATS-6: Less than a month after launch, a partial failure in the roll wheel drive circuitry caused the ACS to become unstable in roll, forcing ATSOCC operations personnel to switch from wheel control to jet control. However, the prospect of using jet propellant full time for the remainder of the mission threatened to significantly shorten the useful life of the spacecraft. Due to the flexibility of the programmable Digital Operational Controller (DOC), ACS engineers were able to reprogram the DOC into a "mixed mode" of operation whereby the pitch and yaw axes operated on wheels and the roll axis utilized jets, thus conserving control gas.

AE-C: Two weeks after launch, one of two redundant memory programmers failed in the "write" mode due to a stuck bit. At day 297, the redundant memory also had a failure due to a stuck bit-----but in the "write" mode. Thus the mission continued due to the fortunate way in which these failures combined.

OSO-7: When OSO-7 was launched, the second stage of the Delta rocket failed to place the spacecraft in the nominal orbit. The spacecraft was sent tumbling and the orbit was approximately 350

kilometers by 570 kilometers, rather than the nominal 556 kilometer circular orbit. After spinup, it was found that the pitch angle exceeded 70 degrees, whereas it should have been near zero. On orbit 6, the project personnel succeeded in achieving normal pitch lock, and the spacecraft was saved. Although the anomaly occurred in the launch vehicle, it was operational flexibility that saved the mission.

OSO-8: Shortly after launch, the two primary (pointed) instruments both degraded one to two orders of magnitude due to contamination. Apparently sensitivity was sufficient that good data was received despite this handicap.

SAGE: Utilizing the same base module as HCMM, this spacecraft has had the same battery degradation problem, and is operating on a reduced data acquisition schedule.

TIROS-N: An unexpected torque disturbance began in revolution 4 which persisted for about 84 minutes and imparted 938 in-lb-sec of angular momentum. On-board reaction wheels were unable to handle the rapid build-up of angular momentum, and the spacecraft went into a tumbling mode. Following uplink modifications to flight software, GN_2 was reactivated on rev. 12 to remove the body rates so that reacquisition and earth lock could be accomplished using the wheels. The cause was attributed to B-nut relaxations due to pyro shock which caused N_2N_4 to leak.

NOAA-A: A disturbance of unknown origin occurred during the first orbit after handover, causing a large attitude perturbation on the spacecraft. The spacecraft's attitude control system functioned properly throughout the event and attitude control was restored within 15 minutes. The most probable cause was failure of the Rocket Engine Assembly-3 thruster valve caused by pressure buildup from heat soakback, thus allowing the hydrazine to leak through the valve to the catalyst bed, producing a torque on the spacecraft.

Magsat: During the launch phase, one of two redundant sublimation timers failed to operate, and the other operated 4 minutes late. Also, the scalar magnetometer, needed to calibrate the vector magnetometer, had a noise problem such that it produced only 20-30% good data. However, only about 15% good data was needed to meet scientific objectives.